Climate Extreme and Crop Diversification: Adaptation to Climate Change in Brazil

by Elena Piedra-Bonilla, Denis Cunha, and Marcelo Braga

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Abstract:

Climatic variability can have a considerable impact on agriculture. In the future, climate variability is expected to increase, as well as the frequency and intensity of extreme events. Crop diversification helps to reduce vulnerability to climate risks. Using fixed-effects panel models for 3813 Brazilian municipalities, we identified the impact of extreme weather on crop diversification; then, we analyzed the effect of climate change on the diversification according to future scenarios. It was found that seasonal averages of temperature and precipitation, Consecutive Dry Days (CDD), Dry Days, and Hot days affect positively on diversification, while for Frost days and Very Heavy Rain Days, there was no effect. The simulations showed that Brazilian municipalities would tend to diversify as the climate scenario becomes more severe. The increase in the percentage of hot days in the period 2045-2065 would increase crop diversification by 0.957% and 0.961%, in the scenarios RCP4.5 and RCP8.5, respectively. These results help to promote public policies that promote adaptation practices in response to adverse effects of climate extreme in agriculture.

KEYWORDS: climate extreme, crop diversification, climate change

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1. Introduction

Climate variability is expected to increase in certain regions of the world, as well as the frequency and intensity of extreme events (IPCC, 2014). In Brazil, the frequency and intensity of drought have increased in the North and Northeast regions (SHUKLA et al., 2019). According to Marengo (2009), for tropical South America, a reduction in the total amount of rain and in the number of humid days is expected, as well as an increase in the number of consecutive dry days until 2030. In addition, an increase in heavy rain is expected in regions such as the west of the Amazon, and the south and southeast of Brazil. There is also evidence of increased frequency of heat waves around Brazil (BITENCOURT et al., 2019; GEIRINHAS et al., 2018), as well as more severe and intense cold waves in most of the southern region (BITENCOURT et al., 2019).

Furthermore, climate variability has considerable impacts on agriculture, especially on countries that depend on agricultural production. There is evidence that abiotic stress due to adverse climatic conditions reduces the productivity of crops in the main agricultural products in the world (MITTLER, 2006; BOYER, 1982). According to Ray et al. (2015), the variability observed globally in the productivity of important crops, such as corn, rice, wheat and soy, depends, around 32% to 39%, on climate variation. Thus, studies that analyze how climate variation affects agricultural production should be highlighted. According to Thornton et al. (2014), there is a relationship between climate variability and changes in the Gross Domestic Product (GDP) in several tropical countries, which depend, economically, on agriculture. To illustrate, Figure 1 shows the relationship between annual variability of precipitation and temperature with the percentage change in Brazil's agricultural GDP in the period 1996-2016. It is noteworthy that the agricultural GDP had drop peaks accompanied by high anomalous values (sometimes positive, sometimes negative) of precipitation and temperature.

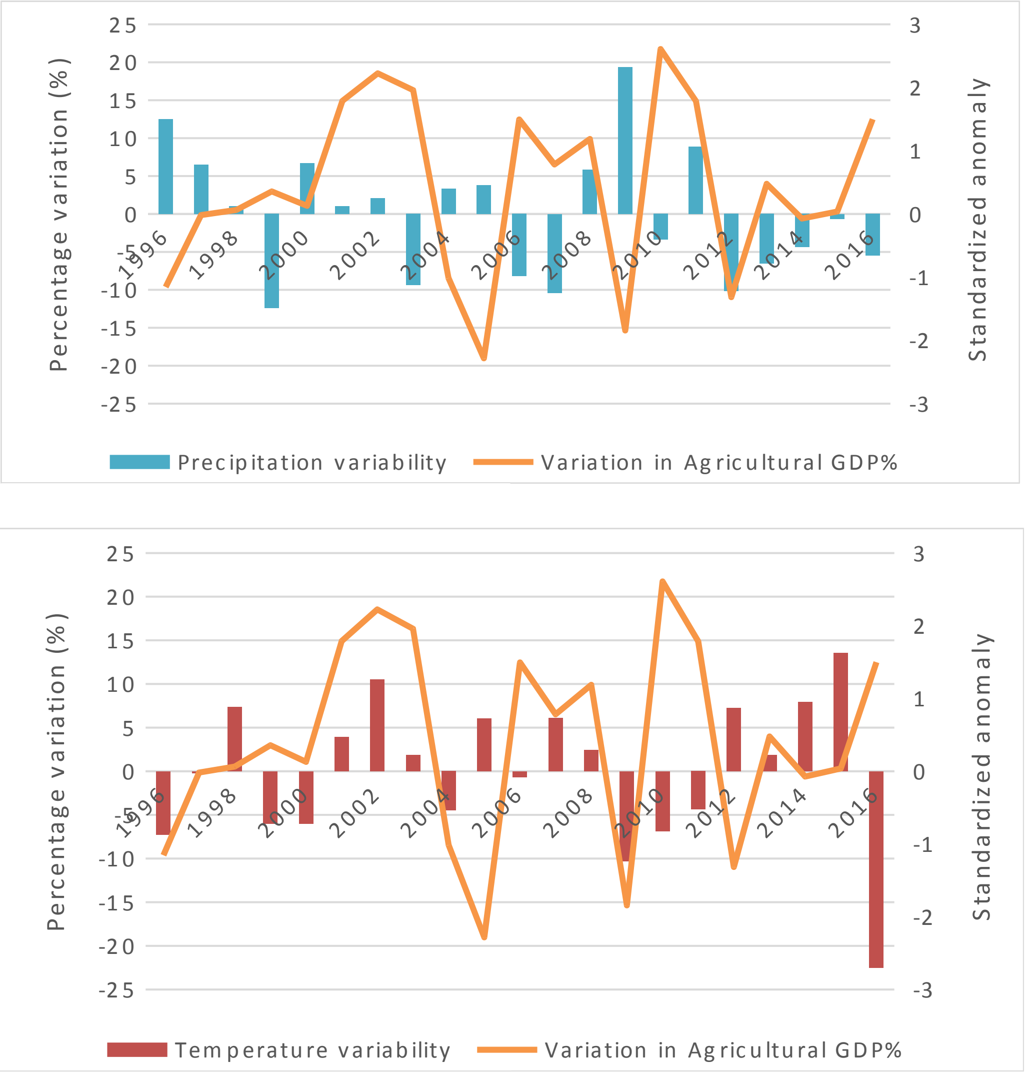

Fig. 1. Relationship between precipitation / temperature variability[4] and agricultural GDP in Brazil (1996 - 2016) Source: Research results, based on data from Global Meteorological Forcing Dataset for land surface modeling (SHEFFIELD; GOTETI; WOOD, 2006) and GDP data from Brazilian agribusiness (CEPEA; CNA, 2020)

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[4] The inter-annual variability of precipitation and temperature is expressed as a standardized anomaly of precipitation and temperature, calculated by the difference between the annual average and the period average divided by the period standard deviation.

However, the negative impacts on agriculture due climate extreme can be reduced if actions to adapt to climate change are carried out. In this way, crop diversification helps to reduce observed or projected climatic risks (HEAL, et al., 2014). Therefore, diversification will be considered an adaptive strategy that helps to reduce negative impacts, as well as, takes advantage of positive effects to maximize the farmer's well-being. Crop diversification promotes economic benefits, such as reducing the variability of farmers' income (JOSHI, 2004) and reducing rural poverty (RENARD; TILMAN, 2019). Additionally, diversification promotes agro-ecological services, since with a greater richness of crop species distributed in space and time, the susceptibility to diseases and pests decreases, reduces soil erosion and improves soil fertility (ALTIERI, 1999).

Regarding climate variables, most researches indicate statistically significant effects on crop concentration. Research converges on the positive impacts of temperature variables on diversification, including their different units of measurement. However, precipitation shocks show ambiguous results (SEO, 2008; DILLON et al., 2015; ASFAW, 2018, ARSLAN et al., 2018). These results depend on the geographical conditions of the regions. However, there exists scant empirical evidence on how farmers respond to different extreme weather. Thus, the present work intends to focus in the effect of climate extremes in the recent past and the future climate change scenarios.

Dealing with this topic in Brazil is especially important, since the country is one of the main food producers and exporters in the world (FAO, 2018). In this context, research that makes it possible to understand changes in land use due to the concentration of agricultural activities is essential. In addition, we can examine adaptive responses to the adverse effects of extreme weather on Brazilian agriculture. Understanding these responses in agricultural adaptation is crucial for prioritizing crop diversification investments and designing risk mitigating strategies depending on the type of extreme event. The results may support the development of public policies to reduce climate vulnerability, through rural extension services or credits. The analysis of the impact of extreme climate events on agricultural diversification could help to understand when this practice becomes relevant to be promoted through technical assistance, credit or research. Additionally, the results can strengthen the existing green agricultural policies, such as the Low Carbon Agriculture Plan (Plano ABC - Agricultura de Baixa Emissão de Carbono) and the National Plan for Agroecology and Organic Production (Plano Nacional de Agroecologia e Produção Orgânica - Planapo) in Brazil.

In this sense, the present research has two main objectives: first, to identify the impact of climate extreme on the crop diversification in Brazilian municipalities in the recent past. Events of climatic variability include, specifically, seasonal averages, frosts in the south, droughts, heavy rains and hot days. Then, understand the effect of future climate change scenarios on the diversification of municipal agricultural production.

The paper is divided into five sections, including this Introduction. The second section presents the empirical strategy and econometric and future simulation specifications. The third section presents the empirical results, while Section 4 presents a discussion and explores policy implications. Finally, Section 5 presents the conclusions.

2. **Empirical Strategy**

In this study, we used a panel data model. Data at Minimum Comparable Area (*Area Mínima Comparavéis* - AMC) level (cross-section) were combined with the years of agricultural censuses 95/96, 2006 and 2017 (time series). In this way, greater precision is obtained in the estimates, the possibility of consistent estimation of models that allow the existence of unobserved effects potentially correlated with the regressors and the possibility of learning more about the dynamics of individual behavior (CAMERON, TRIVEDI, 2005).

Thus, the use of panel data made it possible to study the dynamics of crop diversification over the period of time considered in the study, as well as the effects of climate on this dynamics.

Agricultural diversification at the regional level is an aggregate response to individual farmers' crop choice decisions. This immediate allocation of crops responds to several factors, such as climate variables (ASRAVOR, 2017; RAHMAN, 2016). To determine the causal relationship between climate variability and crop diversification, it would be necessary to carry out a natural experiment that would make the farmer's choice of crops a random decision. So, extreme weather can be considered an ideal experiment, since climate anomalies cannot be predicted exactly. This can also cause exogenous and random variations in the farmers' decision to allocate crops, affecting the level of crop diversification at the municipal level. Then, it was possible to compare the diversification of the municipalities and to know the effect of extremes events without having problems of selection bias (PIEDRA-BONILLA et al., 2020). Therefore, the equation of interest was the impact of the climate extremes on crop diversification:

$$S = f(C, X) \qquad (1),$$

in which vectors of climate variables (C) and control variables (X) affected the Brazilian municipal crop diversification. The climate specifications include five-year moving averages of extreme climate indices for each period of the Agricultural Census 95/96, 2006 and 2017. The five-year moving average was chosen to consider the impact of the medium-term climate on crops perennial and temporary, because a longer period could dilute the effect on these crops (PIEDRA-BONILLA et al., 2020). In this study, we consider the following extreme events: frosts, droughts, hot days and a proxy for floods, because they are linked to abiotic stresses in agriculture (TAIZ and ZEIGER, 2009) Thus, five extreme climate indices were used, recommended by the World Meteorological Organization - WMO's

Expert Team on Sector-Specific Climate Indices (ET-SCI) for the agriculture sector. The definition of the extreme climate indices for this study is presented in Table 1. The indices were calculated using daily values of precipitation, maximum and minimum temperature with data from the Terrestrial Hydrology Research Group (THRG) (SHEFFIELD; GOTETI; WOOD, 2006), obtaining results of annual values considering the base period (1985-2016[5]) and using standardized software (ClimPACT2) (ALEXANDER and HEROLD, 2015).

Table 1. Definition of extreme climate indices

Index code	Name	Definition	Unit	Event type
FD	Frost days	Annual count of days when TN < 0ºC	Days	Frosts
CDD	Consecutive Dry Days	Maximum number of consecutive days with PR<1,0 mm	Days	Maximum length of dry spell
Rn1mm[6]	Number of dry days	Annual count of days when PR <1,0 mm	Days	Dry days
R20mm	Number of very heavy rainy days	Annual count of days when PR ≥ 20 mm	Days	*Proxy* of flood
TX90p	Amount of hot days	Percentage of days when TX > 90th percentile	%	Hot days

Note: TN = minimum temperature, TX = maximum temperature, PR = precipitation

Source: Adapted from ALEXANDER and HEROLD, 2015

2.1. **Extreme events**

Frost days (FD) was considered only for the South region, since it is located below the tropical zone and frost is commonly found in winter (BITENCOURT et al., 2019;

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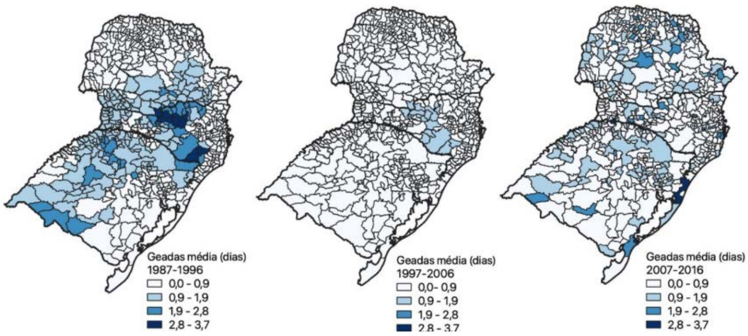
[5] The base period considered a minimum period of 30 years that included agricultural census periods. The daily available temperature and precipitation data were up to 2016. In the data source section there is more detail.

[6] Originally this index indicates the number of personalized rainy days in which rainfall is at least a number of mm specified by the user to account for rainy days. This study was adapted to quantify dry days. However, there is a caveat of showing rain where there is not, since there are pixel resolution problems.

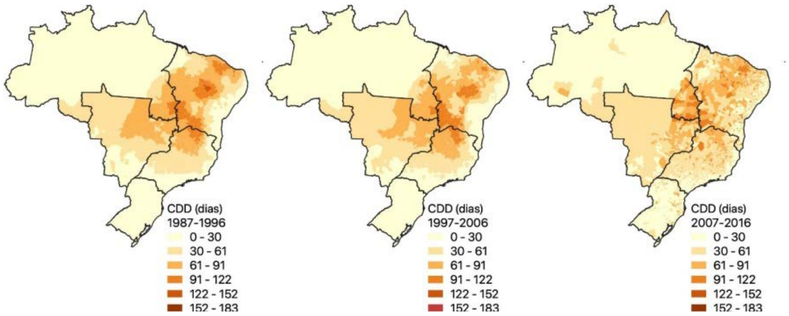
WREGE et al., 2018). Figure 1.a shows the erratic behavior of frosts in the South region of Brazil over three periods (1987-1996, 1997-2006 and 2007-2016). We also used the consecutive dry days (CDD) and the Number of dry days (Rn1mm) to analyze the effect of prolonged drought and intermittent drought on agricultural diversification respectively (Table 1). Severe drought conditions can cause premature plant death, while batch drought conditions affect plant growth and development (KUMAR, 2013). In Brazil, the drought due the severe El Niño phenomenon (2015-2016) caused high mortality of cocoa trees (15%) and decreased cocoa yield by 89% in Bahia (GATEAU-REY et al., 2018). The severe drought in 2012-2013 in Ceará led to a 43% reduction in planted area, resulting in average losses of 75% in crops, and also caused losses in livestock, with the cattle herd mortality rate of 0.33% in 2010 to 3.05% in 2013 (CEARÁ, 2013). Figure 1.b shows the expansion of drought periods between 30 and 61 days in the Midwest, Southeast and South regions, while the Northeast shows an increase in the dispersion of high CDD values (> 122 days) over 1987-2016 years. In Figure 1.c, it is highlighted that the days without precipitation have increased in the North and Center-West. Conversely, Figure 1.d shows the decrease of very heavy rainy days in the period from 2007 to 2016. Flood-sensitive crops are harmed, considerably reducing their productivity.

Furthermore, prolonged exposure to extreme temperatures, especially during flowering, harms most plants, which can cause losses in agricultural production (TAIZ e ZEIGER, 2009). In Brazil, the study by Gusso et al. (2014) showed that heat waves can potentially increase the effects of drought and reduce soybean productivity in the South. Thermal stress also affects livestock production. For example, severe exposures of thermal stress can cause reductions in productivity (20%) of cow's milk in southern Brazil (GARCIA et al., 2015). Figure 1.e shows that the amount of hot days has increased over the three periods (1987-1996, 1997-2006 and 2007-2016), especially in the last period (2007 - 2016).

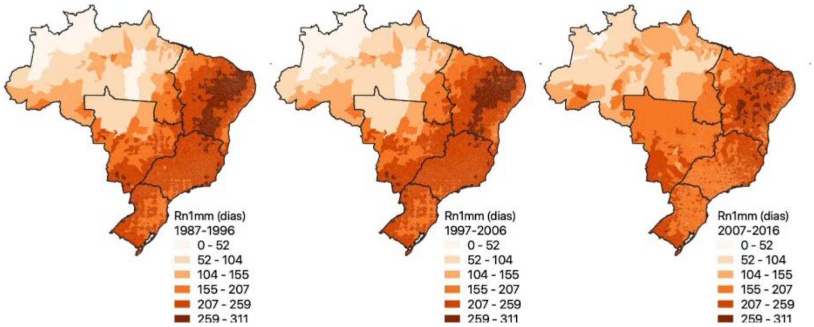
a. Frost days (FD)



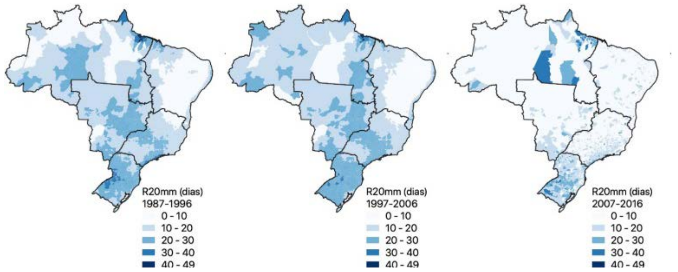
b. Consecutive Dry Days (CDD)



c. Dry days (Rn1mm)



d. Very heavy rainy days (R20mm)



e. Hot days (TX90p)

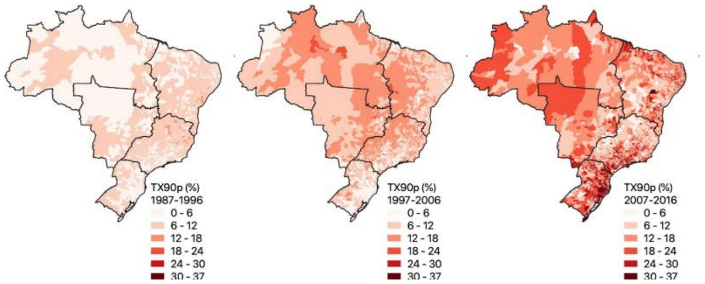


Fig. 2. Extreme climate indices in Brazil over the periods 1987-1996, 1997-2006 and 2007-2016. Source: Research results, based on data from Global Meteorological Forcing Dataset for land surface modeling (SHEFFIELD; GOTETI; WOOD, 2006)

2.2. Econometric model

The empirical analysis was based on a panel econometric model with fixed effects in which the agricultural diversification of Brazilian municipalities is affected by the climate and other socioeconomic, agricultural and market characteristics. This approach follows a general model developed by Benin et al. (2004) and Van Dusen & Taylor (2005). Thus, the complete version of the equation of interest (1), which was previously presented, is:

$$S_{it} = \beta C_{it} + \gamma SE_{it} + \delta A_{it} + \zeta M_{it} + \mu_i + \theta_{rt} + \varepsilon_{it}, \qquad (2)$$

where S_{it} represents the Simpson crop diversification index in municipality i and in year t, C_{it} represents various specifications of climate extreme in municipality i and in year t. SE_{it} is the vector of the socioeconomic characteristics of the municipality i and in year t, A_{it} is the vector of the agricultural characteristics of the municipality i and in year t, M_{it} is the vector of the market characteristics of the municipality i and in year t, μ_i represents the effects municipalities, capturing fixed spatial characteristics, observed or not, removing the shock of many possible sources of omitted variable bias (DELL, JONES, OLKEN, 2014). θ_{rt} represents the fixed effects of year t and state r, neutralizing any common state trends and ensuring that relationships of interest are identified by idiosyncratic local shocks. ε_{it} is the independent and identically distributed error term (*iid*) in municipality i and in year t, with mean 0 and variance σ.

The Simpson index is adapted from ecological indexes of species diversity, representing the concentration of species (MAGURRAN, 2004). This index considers how much each agricultural activity contributes to the total agricultural income of the municipality (SAMBUICHI et al., 2016). Thus, agricultural and livestock products are taken into account:

$$S_l = 1 - \sum_{j=1}^{N} \alpha_k^2 \, 0 \leq S_l \leq 1 \qquad (3),$$

where α_k is the proportion of the Gross Value Production of each agricultural product in the total agricultural Gross Value Production of the municipality. The value 1 indicates perfect diversification and the value 0 indicates perfect specialization (a single product).

For climate variables, six specifications were used to analyze the effect of extreme weather events (C_{it}):

i. **Frosts:** five-year moving average of the FD index, as well as the five-year moving average of winter precipitation, since there is a correlation (0.52 ***) between temperature and precipitation (AUFFHAMMER, 2013). Winter precipitation was used because most of the frosts occur in that season. These variables were only used for the South region.

ii. **Longest annual drought period:** the five-year moving average of the CDD index, as well as the five-year moving average of the annual average temperature. The correlation between these two variables was 0.35 ***.

iii. **Dry days**: the five-year moving average of the Rn1mm index, as well as the five-year moving average of the annual average temperature. The correlation between these two variables was 0.01 *.

iv. **Flood Proxy:** the five-year moving average of the R20mm index (Number of very heavy rain days), as well as the five-year moving average of the annual average temperature. The correlation between these two variables was -0.37 ***.

v. **Hot days:** the five-year moving average of the TX90p index (Number of hot days), as well as the five-year moving average of annual accumulated precipitation. The correlation between these two variables was -0.12 ***.

The independent variables were measurements of the vectors shown in the right part of equation (2), according to the results in Table 2. The technical assistance variable is considered an important resource for the dissemination of information on agricultural practices (RAHMAN, 2016), which can influence the adoption of new technologies and also the diversification of cultures. According to Benin et al. (2004), larger agricultural establishments can produce more crops. The irrigation variable can decrease diversity through uniform humidity conditions (BENIN et al., 2004), as well as being an investment directed to intensive crops. In the market variable, the number of establishments that produce corn was used, considered a proxy to control the effect of the demand of the main crops. The value of soy production was not considered because only in 1877, 1360 and 1832 Brazilian municipalities in the 1995/1996, 2006 and 2017 censuses, respectively, reported these data, causing considerable loss of observations. However, most of the Brazilian corn production is carried out in double cropping systems (soybean-corn) (ABRAÃO; COSTA, 2018), so we are indirectly taking soybean into account.

2.3. Simulations of the impact of climate change on crop diversification

In order to analyze how the diversification of municipal agricultural production will respond in future periods to the climate change scenarios expected by the IPCC, we simulated the consequences of these scenarios on crop diversification behavior, using the parameters estimated by the equation of interest of this research (1) (SEO; MENDELSOHN, 2008). Thus, according to equation (4), the crop diversification index of the Brazilian municipalities ($\widehat{S_{iBASE}}$) was estimated, considering extreme climate indexes projected for the base year ($C_{i,BASE}$), along with the parameters estimated by equation (2):

$$\widehat{S_{iBASE}} = \beta C_{i,BASE} + \gamma SE_{it} + \delta A_{it} + \zeta M_{it} + \mu_i + \theta_{rt} + \varepsilon_{it} \qquad (4)$$

The base year was the last year of the period included in this study, 2016. In this way, the existing bias between the expected values and the observed values of the considered climatic variables was eliminated. In addition, the estimate was made for the period between 1986 and 2005, which is the base period specified by the IPPC's Fifth Assessment Report (AR5). The baseline scenario assumes that farmers will continue to produce their current crops if the climate remains unchanged. In other words, no other possible reasons have been modeled for why the choice of cultures may change in the future. Only the effects of climate change were observed separately from the effects of the other variables, although the other variables are expected to vary over time (SEO; MENDELSOHN, 2008).

Then, the agricultural diversification index ($\widehat{S_{iFUTURE}}$)) was estimated, considering the temperature and precipitation averages and the extreme climate indices projected for future scenarios ($C_{i,FUTURE}$), established by the IPCC (2013) for the averages of two periods: beginning (2016-2035) and mid (2046-2065) of the 21st century, according to the following equation:

$$\widehat{S_{iFUTURO}} = \beta C_{i,FUTURO} + \gamma SE_{it} + \delta A_{it} + \zeta M_{it} + \mu_i + \theta_{rt} + \varepsilon_{it} \qquad (5)$$

When using the parameters estimated in equation (5) to estimate the future crop diversification index, we assumed that the relationship between climatic variables and the diversification index will remain constant until the last future period used in the simulations. To avoid using a year projection with an outlier, we used average data for periods of time. Finally, the rate of change in diversification was calculated in response to changes in temperature and precipitation expected by the following equation:

$$\%\Delta S_{it} = \frac{\widehat{S_{iFUTURE}} - \widehat{S_{iBASE}}}{S_{iBASE}} x\, 100 \qquad (6)$$

To perform the simulations for the scenarios RCP4.5 and RCP8.5, we obtained the climate data from four General Circulation Models (GCM - General Circulation Model): HadGEM2-ES - Hadley Center Global Environmental Model version 2; MIROC-ESM - Model for Interdisciplinary Research on Climate; and MRI-CGCM3 - Meteorological Research Institute Coupled Atmosphere – Ocean General Circulation Model version 3. According to Pires et al. (2016), the HadGEM2-ES model has the capacity to correctly simulate the seasonality of precipitation in several regions of Brazil, according to evaluations of simulated historical precipitation.

2.4. Data source

This study used as units of observation the Minimum Comparable Areas (AMC) for allowing intertemporal comparisons of the same geographic area, since the number of Brazilian municipalities increased over the years (EHRL, 2017). For this, we made compatible municipalities from the Demographic Censuses from 1980 to 2010, following the methodology proposed by Ehrl (2017).

The data used for the construction of the Simpson index were extracted from the Agricultural Censuses 1995/1996, 2006 and 2017 from the Brazilian Institute of Geography and Statistics – IBGE. We considered the Gross Value Sold of heads of cattle, pigs, poultry and the Gross Value Production of horticulture, permanent crops, temporary crops, forestry and plant extraction at the municipal level. These products were selected due to the limited data from the 1995/1996 Census of Agriculture, despite the fact that the other Census of Agriculture has information on more agricultural products. These municipal data were then aggregated into AMCs. However, several AMCs did not display data on agricultural products at all times, resulting in an unbalanced panel. From the 1995/1996 Census of

Agriculture, data on agricultural products were extracted, which resulted in 3,809 AMCs, while they constituted 3,798 AMCs and 3,813 AMCs in 2006 and 2017, respectively.

The daily georeferenced data of maximum and minimum temperature, as well as precipitation, were extracted by the Terrestrial Hydrology Research Group (THRG) (SHEFFIELD; GOTETI; WOOD, 2006). The database was built by combining global data based on surface observations with the NCEP – NCAR (National Center for Environmental Prediction / National Center for Atmospheric Research) reanalysis. The original data used have a resolution of 0.25º × 0.25º (spatial resolution 28km) of daily precipitation (mm) and daily temperature (C), for the period from 1985 to 2016. However, for the analysis at the AMC level , the data were interpolated to a resolution of 30 meters. Thus, 3826 AMCs remained, since three observations were excluded because they did not have climatic data in their respective pixels. It is worth mentioning that the temperature and precipitation data provided by THRG are up to the year 2016. Thus, the impact of the climate did not consider the year 2017. However, the moving averages from five years ago can model the crop choices of the farmers in relation to climate variability (CHO; MCCARL, 2017).

The data for the variables representative of the socioeconomic, agricultural and market characteristics of the Brazilian municipalities were also extracted from the Agricultural Censuses 1995/1996, 2006 and 2017. This information was also aggregated in AMCs.

Future climate data were extracted from the General Circulation Models: HadGEM2-ES; MIROC-ESM; and MRI-CGCM3. In the same way as the observed climatic data, the future data used have a resolution of 0.25º × 0.25º of daily precipitation (mm) and daily temperature (C), for the period from 2016 to 2065. Therefore, four AMCs were excluded from the simulations, since there was a lack of data in the corresponding pixels.

3. Results

3.1. Descriptive statistics

Table 2 summarizes the data for the variables in equation (2) for the years 1996, 2006 and 2017. Regarding the variables of socioeconomic, agricultural and market characteristics, it is noteworthy that the Brazilian average of the number of producers with legal status of the farm has increased. The number of producers who received technical assistance increased in 2006, but declines slightly in 2017. In addition, the average farm size has decreased over the periods. At the same time, the number of farms with corn production in 2017 was reduced by more than 55% compared to 1996. In the last three decades, corn production has been concentrated in regions with higher productivity, especially in the Center- West and South and in the MATOPIBA area (OLIVEIRA & GASQUES, 2019).

Table 2. Summary Statistics

Variable	1996		2006		2017	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Simpson Index	0.69	0.20	0.61	0.22	0.63	0.21
Socioeconomic characteristics						
Technical assistance (unit)	238.62	494.99	299.25	556.35	262.99	488.34
Legal status of farms (unit)	941.76	1390.97	1031.22	1563.97	1072.78	1739.89
Agricultural characteristics						
Farm size (ha)	95.62	178.97	77.18	135.03	77.62	127.05
Irrigation (unit)	74.26	180.83	86.76	216.69	132.04	335.30
Market characteristics						
Maize farms (unit)	663.61	1187.94	530.45	983.90	432.35	863.44
Climate characteristics						
FD (days)	0.10	0.36	0.02	0.09	0.26	0.77
Rn1mm (days)	229.62	35.29	227.05	34.74	208.48	33.58
R20mm (days)	17.86	8.02	16.45	7.03	8.20	7,.94
TX90 (% days)	7.07	2.96	9.96	4.19	19.95	14.84
CDD (days)	36.80	23.86	33.74	21.31	41.01	27.75
Annual temperature ºC	23.77	2.60	24.16	2.54	24.06	2.66
Annual rainfall (mm)	1407.93	469.22	1359.94	424.30	1337.29	511.09

Source: Research results

The Simpson index decreased over the years of interest, showing only a slight increase in the year 2017. The rate of decrease in Brazilian diversification was -8.7% in 1996-2017. However, the index values were still found in the Diversified category even with the decreasing trend. Furthermore, the regions showed particular developments in crop diversification (Figure 3). The South and Northeast regions maintained the highest values of diversification in the three Agricultural Censuses, while for the Center-West region it was the opposite. These results are related to the farm size, because the South and Northeast regions have a strong presence of family farming with small production, contrary to the Midwest region, which has large farms specialized in few cultures (DE CASTRO, 2014).

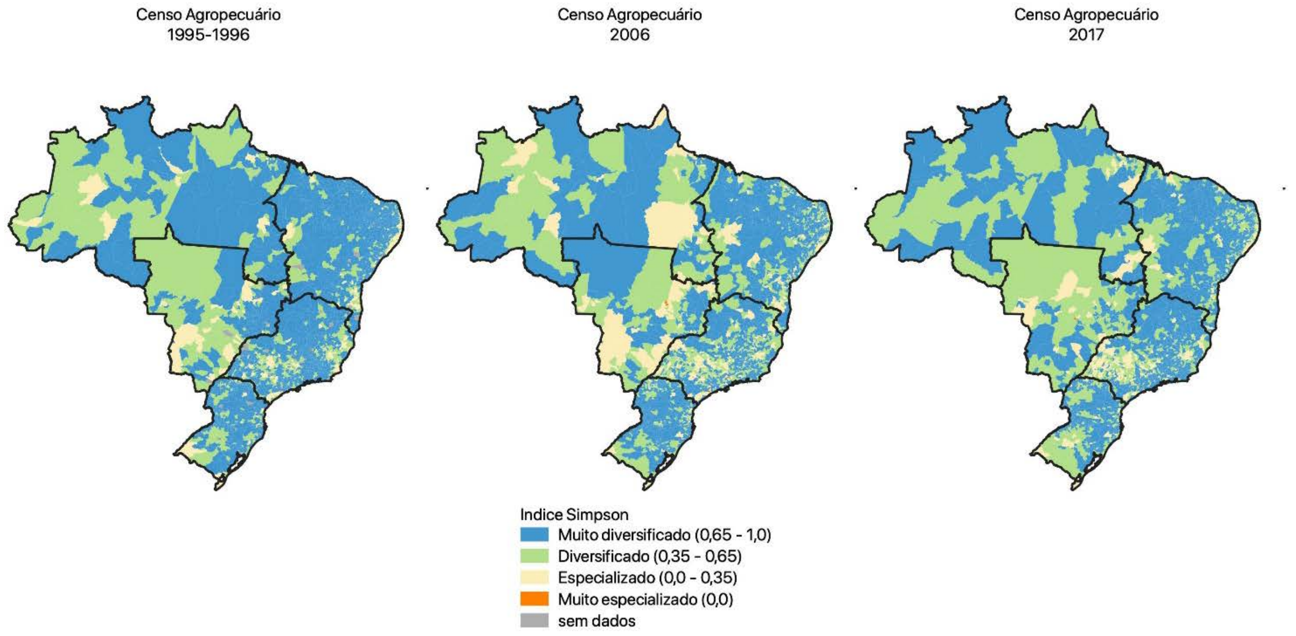


Fig. 3. Evolution of agricultural diversification (Simpson Index) in the 1995/1996, 2006 and 2017 Agricultural Censuses

Source: Research results

Regarding the climate variables, it is worth noting that the moving averages of dry days (below 1mm of precipitation daily) decreased slightly in Brazil. Likewise, the days with heavy rain decreased considerably in the last period. But the number of hot days grew a lot, especially in 2017, increasing by around 182% compared to the 1996 moving average.

Similarly, the consecutive dry day moving average has increased. On the other hand, the moving averages of frosts in the South region have also been increasing. The means of annual temperature are similar over the period, but the rainfall annual has decreased in the same period.

3.2. Impacts of extreme weather events on crop diversification

Table 3 shows the effects of extreme weather events on crop diversification in Brazil. In model (1), it was observed that frosts (FD) had a negative relationship with crop diversification in the South, but the variable was not statistically significant. Therefore, diversification is not the main strategy to mitigate the risks of frosts. The consecutive dry days index (CDD) positively affected crop diversification at the 10% level of significance in the model (2). This model only used fixed year and AMC effects. The dry day's variable (Rn1mm) was positive and statistically significant at 1% in the model (3). The very rainy days (R20mm) negatively affected crop diversification; however it was not statistically significant in the model (4). This result may be related to the fact that measures to reduce the negative effects of floods are more linked to other methods, such as flood forecasting systems, channel infrastructures and, or, agricultural drains, the location of the productive systems that avoid being in areas of recurrent flooding.

In model (5), the increase in the rate of Hot Days (TX90p), on average, produces an increase of 0.000704 in the level of diversification. The coefficients of the variable of interest (TX90p) were higher than the rest of the variables. Similarly, the results by Dillon et al. (2015) revealed that the number of crop groups harvested has a positive relationship with the degree day shocks.

Table 3. Effects of climate extreme indices on crop diversification in Brazil

Variable	(1)	(2)	(3)	(4)	(5)
Technical assistance	1.45e-05	9.22e-06	1.91e-05**	1.96e-05**	2.00e-05**
	(1.00e-05)	(7.75e-06)	(8.36e-06)	(8.32e-06)	(8.36e-06)
Legal status of farms	2.85e-06	4.01e-06	-3.20e-06	-2.46e-06	-2.51e-06
	(1.40e-05)	(3.80e-06)	(4.30e-06)	(4.31e-06)	(4.30e-06)
Irrigation	4.14e-05	3.90e-05***	1.52e-05	1.34e-05	1.38e-05
	(3.96e-05)	(1.04e-05)	(1.01e-05)	(9.99e-06)	(1.00e-05)
Farm Size	-0.000284	-0.000236***	-0.000243***	-0.000245***	-0.000243***
	(0.00030)	(3.53e-05)	(3.56e-05)	(3.59e-05)	(3.58e-05)
Maize farm	6.34e-06	6.21e-06*	1.19e-05***	1.21e-05***	1.18e-05***
	(8.71e-06)	(3.32e-06)	(3.80e-06)	(3.82e-06)	(3.80e-06)
FD	-0.00541				
	(0.00496)				
Winter precipitation	0.000178*				
	(0.00010)				
CDD		0.000161*			
		(9.46e-05)			
Rn1mm			0.000229***		
			(7.82e-05)		
R20mm				-1.20e-05	
				(0.000358)	
Annual temperature		0.00182*	0.00346***	0.00371***	
		(0.00103)	(0.00107)	(0.00109)	
TX90p					0.000704***
					(0.000179)
Annual rainfall					-3.93e-06
					(6.63e-06)
Constant	0.681***	0.648***	0.508***	0.550***	0.630***
	(0.0249)	(0.0250)	(0.0299)	(0.0278)	(0.0124)
Fixed effects state/year	YES	NO	YES	YES	YES
N	2,009	11,420	11,420	11,420	11,420
R-squared	0.088	0.083	0.144	0.143	0.144
F Statistic	12,75***	11,34***	236,09***	237,29***	236,66***
Number of AMC	671	3,818	3,818	3,818	3,818

Note: Robust standard errors are in parentheses;

Significance: *** p <0.01, ** p <0.05, * p<0,1

Source: Research results

In general, it is emphasized that some controls, such as technical assistance, size of the establishment and the demand Proxy for important crops (corn), were statistically significant in all models, except by the frosts. Therefore, they are considerable factors in the allocation of crops in Brazil. Access to technical assistance and corn production had positive effects on diversification across all models. Thus, the role of rural extension services becomes important, especially in small farms, to disseminate agro-ecological practices, resilient to extreme weather events, which are expected to increase in intensity and frequency in the future. Furthermore, the results show that diversification is not contrary to the production of main crops, such as corn.

Furthermore, it was observed that the farm size has a negative influence on diversification in all estimated econometric models (except when the model includes frosts). Then, the small producer is more likely to diversify as a way of reducing its income variability, which is much greater than the large one, which is less vulnerable to shocks in its agricultural production.

3.3. Future projections of the impact of climate change on agricultural diversification

For the analysis, only the extreme weather events that obtained statistically significant coefficients in the models estimated in the previous section were considered, such as, the consecutive dry days, the dry days and the hot days. For both frosts in the South and for very rainy days in Brazil, no statistically significant effects on diversification were observed, so no future projections were made.

Figure 4 shows the expected evolution (2016-2065) of average annual temperature and accumulated precipitation in Brazil. It is noteworthy that there is an increasing temperature trend in the three projections of the global climate models (HadGEM2-ES; MIROC-ESM and MRI-CGCM3) and in the two GHG emissions scenarios (intermediate - RCP4.5 and extreme - RCP8.5). The MRI-CGCM3 projections show the worst temperature scenario, as well as the lowest accumulated precipitation values in relation to other climate models. According to the IPCC (2014), it is very likely that extreme hot temperatures will be more frequent as global warming increases, as well as, it is plausible that heat waves occur more frequently and last longer. We also observed that there is no trend in the expected evolution of annual accumulated precipitation. The changes in precipitation will not be uniform throughout the 21st century, but an increase in the contrast in precipitation between wet and dry regions and between rainy and dry seasons is expected (IPCC,2013).

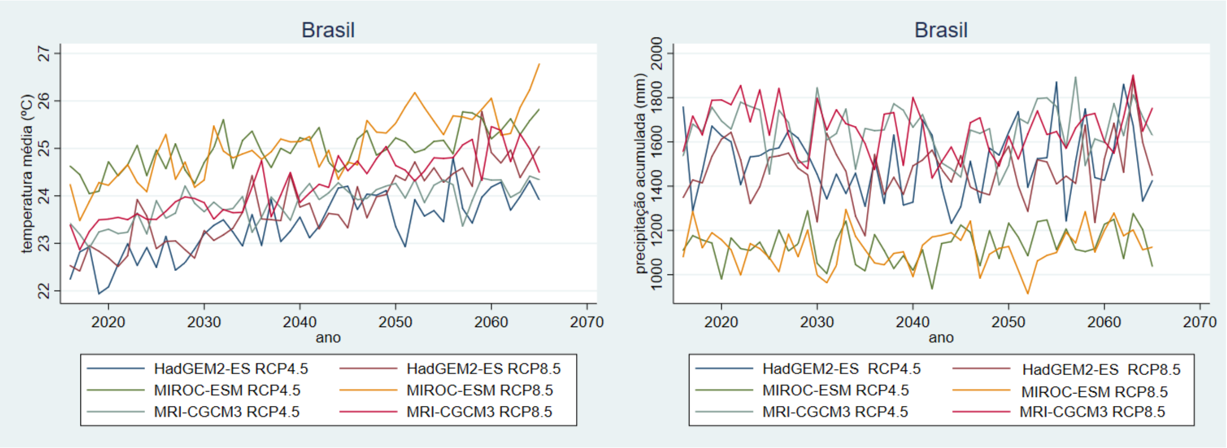


Fig. 4. Expected evolution of the average annual temperature (ºC) and accumulated precipitation (mm) in Brazil (2016-2065) Source: Research results, based on data from HadGEM2-ES - Hadley Center Global Environmental Model version 2; MIROC-ESM - Model for Interdisciplinary Research on Climate; MRI-CGCM3 - Meteorological Research Institute Coupled Atmosphere – Ocean General Circulation Model version 3

To simulate the impacts of climate change on future crop diversification in Brazil, we used the statistically significant estimates of the parameters in the previous section. Thus, the CDD, Rn1mm and TX90p indices were considered. Most of the simulations with the climate specifications were obtained from the estimated coefficients of the econometric models that included the fixed effects for AMCs and state / year, since they showed better adjustment, according to equation (2), except for the CDD model. Finally, the base ($\widehat{S}_{BASE}$)

and future ($\hat{S}_{iFUTURE}$) crop diversification indices were estimated using equations (4) and (5), respectively.

Table 4 summarizes the impact of climate change on crop diversification in Brazil in the periods 2016-2035 and 2046-2065 in the three projections of the General Circulation Models (HadGEM2-ES; MIROC-ESM and MRI-CGCM3) and in two scenarios of GHG emission (RCP4.5 and RCP8.5). The results were calculated using equation (6) of the rate variation in crop diversification ($\%\Delta S_{it}$) considering CDD, Rn1mm and TX90p indices projected for the base year and future scenarios. Additionally, the *t* test was applied to compare equality of means in the variation of diversification between different climate specifications, in both emission scenarios. The specification of hot days was chosen as a basis for comparison with the other climatic variables since the estimated coefficients of the TX90p index were statistically significant at 1% in Table 4, as well as that there is a high probability that the maximum extreme temperatures will be more frequent (IPCC, 2014). It is noteworthy that, in most cases, there is no statistically significant difference in the means. Thus, the econometric models used in the simulations are shown to be robust.

The results indicate that in the period 2016-2035, crop diversification in Brazil would increase little and could even decrease, especially in the extreme scenario (RCP8.5). In the results of the simulations presented in Table 15, it is observed that the increase in the rate of hot days in the first period could lead to a slight decline in the level of diversification of -0.003% and -0.176% in the scenarios RCP4.5 and RCP8.5, respectively. To illustrate, Figure 5 shows the diversification changes that could take place in the early and mid-21st century under future TX90p climate scenarios. The TX90p index was chosen as the main analysis specification because the increase in temperature is the global trend with the highest probability of occurrence.

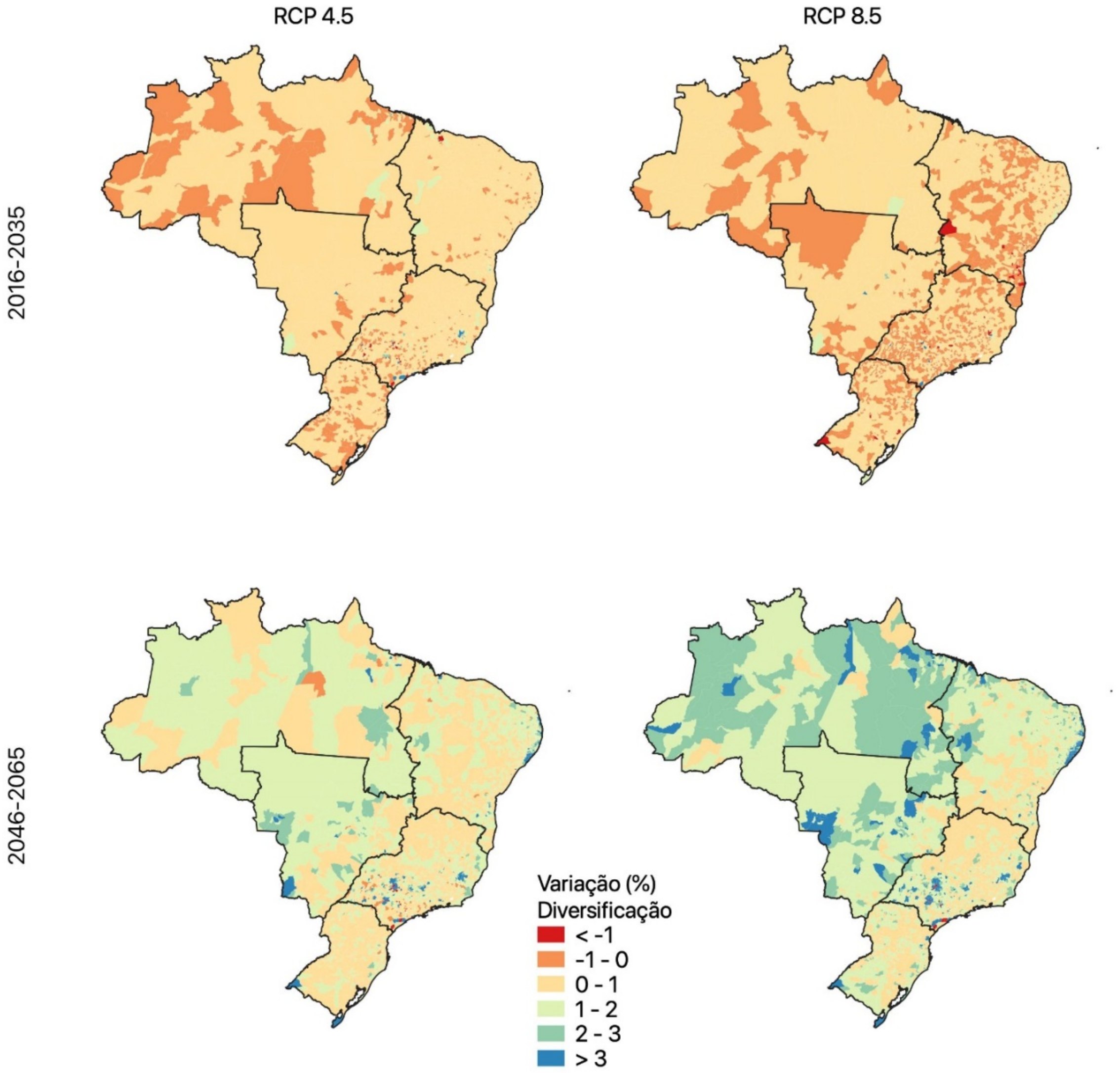


Fig. 5. Rate variation in crop diversification in Brazil under future TX90p climate scenarios

Note: The values were calculated from the average of the three projections of the global climate model (HadGEM2-ES; MIROC-ESM and MRI-CGCM3) and in two emission scenarios (RCP4.5 and RCP8.5), from the calculated averages of the TX90p index.

Source: Research results

On the other hand, in the period 2045-2065, diversification would have a positive variation, albeit of low magnitude, in most cases (Table 4). In simulations of the TX90p increment, the average percentage variation of crop diversification would be 0.957% and 0.961%, in the scenarios RCP4.5 and RCP8.5 respectively. As shown in Figure 5, the greatest increase in diversification in this period would occur in the scenario of global warming with high GHG emissions (RCP8.5). It is also notable that the greatest rate variation in the level of crop diversification would occur in the Midwest and North regions.

Table 4. Effect of climate change scenario on the variation in crop diversification ($\%\Delta S_{it}$) in Brazil

Climate models	**Rate variation crop diversification ($\%\Delta S_{it}$)**					
	CDD		**Rn1mm**		**TX90p**	
	RCP4.5	**RCP8.5**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
2016-2035						
HadGEM2-ES	0.212	-0.037	9.462	0.062	0.427	0.599
	(0.542)	(0.488)	(520.197)	(1.649)	(11.57)	(23.9048)
MIROC-ESM	-0.293	0.387	0.027	-0.213	-0.087	-1.069
	(0.538)	(0.583)	(1.754)	(40.744)	(20.474)	(87.886)
MRI-CGCM3	0.04	-0.2***	-0.199	-0.42***	-0.35	-0.06***
	(0.467)	(0.713)	(7.144)	(3.886)	(23.564)	(1.444)
mean	-0.014	0.038	3.097	-0.189	-0.003	-0.176
	(0.289)	(0.291)	(173.329)	(12.981)	(11.713)	(30.266)
2046-2065						
HadGEM2-ES	0.724	0.545	20.111	1.172	1.317	1.368
	(0.831)	(0.614)	(1141.966)	(4.217)	(25.165)	(53.669)
MIROC-ESM	-0.117*	0.82	0.304	-0.583	0.623	-0.026
	(0.584)	(0.799)	(3.069)	(137.809)	(26.557)	(121.3)
MRI-CGCM3	0.324***	0.437***	0.515***	0.873***	0.932	1.541
	(0.562)	(0.728)	(3.888)	(8.908)	(2.178)	(7.922)
Mean	0.31***	0.600	6.977	0.487	0.957	0.961
	(0.404)	(0.487)	(380.693)	(48.934)	(12.429)	(47.792)

Note: Standard deviations are in parentheses; Significance in the difference between model means: *** p <0.01, ** p <0.05, * p <0.1

Source: Research results

In general, it is observed that the scenario without additional efforts to restrict GHG emissions (RCP8.5) predicts the lowest values in the rate variation of diversification in the first period, while, in the second period, the variation would show the highest values. AMCs would tend to diversify further as the climate scenario becomes more severe. Additionally, the HadGEM2-ES model anticipates the highest percentage values in the variation of diversification in both periods and emission scenarios.

4. Discussion

Regarding the impact of frosts in the South, non-statistically significant parameters can be justified since the diversification strategy is not considered as a common practice to manage this type of risk. It would imply, above all, using species or varieties that are tolerant at low temperatures or tree with taller species to help reduce heat-related losses. This would limit the selection of species diversity only for that extreme climatic event. In addition, there are other methods to prevent damage caused by frosts that do not depend on the selection of specific species, such as altering sowing dates, planning crops according to topography, using greenhouses or covering seedlings and plants, irrigation and, in the case of livestock, heaters and construction of stables with cover for the protection of the cold for animals. Thus, agricultural diversification is not the main strategy to mitigate the risks of frosts.

With regard to prolonged droughts (CDD), crop diversification is not considered as the main response to the adverse effects of this extreme event in Brazil. Possibly, irrigation is considered the main practice in the choice to reduce the risks of droughts, since there is evidence that has responded to the reduction of precipitation in Brazil (CUNHA et al., 2015). However, it is worth mentioning that adequate adaptation planning should include synergy between adaptive practices (TEKLEWOLD et al., 2017). For example, adopting diversification in conjunction with irrigation can help to overcome shocks related to prolonged drought. According to Renard and Tilman (2019), the diversity of agricultural species associated with irrigation increases the temporal stability of national crop production, contrary to the instability of precipitation and temperature. On the other hand, diversification has been effective in reducing the demand for irrigation water and mitigating GHG emissions in rice production in the Philippines (JANZ et al., 2019), as well as in mitigating the adverse effects on agricultural productivity due to rainfall deficit in India (BIRTHAL; HAZRANA, 2019) and in the United States (BOWLES et al., 2020).

The results also indicated that diversification is not being considered as a strategy to reduce agricultural vulnerability caused by flooding in Brazil. In addition, diversification may not be affected by the fact that there is a decreasing trend in days with very heavy rains in all Brazilian regions (Figure 2.d). However, the agroforestry system (SAF), a form of crop diversification, has been recognized as a practice that mitigates the effects of floods, as forests are not easily damaged by flooding, prevent soil erosion and reduce water flow (QUANDT; NEUFELDT; MCCABE, 2017). Therefore, more research and development is needed to understand how SAFs can be resilient to intense rain events in Brazil.

Our results suggest that AMCs have adopted the diversity of agricultural activities as a strategy for adapting to heat shocks, considerably increased in all Brazilian regions. These results are similar to those found in the study by Birthal and Hazrana (2019), in which the thermal stress shocks of the previous year increased the diversification of cultures of Indian farmers. Similarly, the results of Dillon et al. (2015) revealed that the number of crop groups harvested has a positive relationship with the degree day shocks.

In relation to future climate change simulations, the future decrease in crop diversification in the period 2016-2035 (Table 5 and Figure 5) would reflect a continuation of the past evolution, which was decreasing from 1995/96 to 2017. However, in the second period (2046-2065) there would be a change in direction in which diversification would increase in Brazil, albeit slightly (Table 5 and Figure 5). Then, in this period, crop diversification would start to gain prominence as a strategy for adapting to climate change. These results are similar to those found in Latin America by Seo (2010), whose simulations indicate that the increase in mixed establishments (ILP) would occur in hot scenarios, both dry and slightly humid, until 2060.

Furthermore, the increase in the rate variation in diversification in the Midwest in the period 2045-2060 in both scenarios of GHG emissions (RCP 4.5 and RCP8.5) (Figure 5), shows that this region that has been characterized by the specialization of cultures , such as corn, soy, sugar cane, would change their technologies to more resilient agricultural practices. For example, this region has adopted the system of no-till in grain crops (ROMEIRO, 2014) that requires the rotation of diversified crops for its correct functioning in the long term.

However, the small growth in crop diversification from the middle of the 21st century would not be enough to reduce vulnerability in the face of climatic scenarios. The benefits of resilience acquired from diversification improve in the long term (BOWLES et al., 2020; BIRTHAL; HAZRANA, 2019), so pressing public policies are needed to help increase the diversity of cultures in Brazil to improve its potential to reduce climate risks over time. In this context, it is important to discuss, on the one hand, the factors that have favored the concentration of crops from the public sector, but on the other hand, there are different current public strategies that can encourage agricultural diversification as a Brazilian agricultural adaptation to climate change.

In Brazil, monocultures on large farms destined for export have had economic importance since colonial times, except in the Northeast because; their climatic conditions have been less favorable (FAUSTO & FAUSTO, 1994). However, it is only after 1980, that the country ceases to depend on food imports after several public policies. Credit, research and the rural extension of various institutions were consolidated and boosted agricultural production around the 70s of the last century (VIEIRA FILHO & FISHLOW, 2017). However, the development of agricultural technology was mainly focused on grain production with the intensive use of mechanization, fertilizers and pesticides (ALVES et al, 2013). This logic was influenced by the practices and technologies of the Green Revolution, expanded in industrialized countries, through the improvement of new varieties of grains, the intensive use of pesticides, mechanization and irrigation (DE ANDRADES & GANIMI, 2007). Thus, the P&D was focused on the specialization of crops, influencing equally in technical assistance and rural credit. So, public policies have promoted this logic of monocultures and a reduction in the diversity of cultures.

However, P&D has started to focus on the development of sustainable technologies, after pressure from civil society and scientists, indicating the negative environmental impact, monocultures and the intensive use of chemical inputs and machinery. In 2009, Brazil established the National Policy on Climate Change, in which the agricultural sector is contemplated through the Low Carbon Emission Agriculture Plan (ABC Plan), established in the following year until 2020. The ABC Plan has organized actions to be taken for the adoption of sustainable production technologies, in order to meet the country's GHG emissions reduction commitments in the agricultural sector. Within the actions, the concept of diversification is not considered as such, but it has several forms of diversification used in the programs, such as Crop-Livestock-Forest Integration (iLPF), Agroforestry Systems (SAFs), and Rotation, Consortium and, or Crop succession as part of the No-Tillage Systems (SPD). According to MAPA (2018), it is observed that the ABC Plan has driven agricultural diversification through its programs, even exceeding the commitments established at the beginning of the programs, since the iLPF reached 146% of the goals. So, it is important that the ABC Plan continues in a new phase to reinforce and expand resilient and mitigation technologies, such as diversification. According to Souza Piao et al. (2021) and Vinholis et al. (2021), in order to strengthen the adoption of the ABC Plan technologies, it is necessary to improve the rural extension service in the diffusion of sustainable technologies to producers. These results accompany the positive effects of technical assistance on agricultural diversification observed in most climate specifications.

On the other hand, remembering that small establishments are more willing to diversify their agricultural production in Brazil, it is also important to discuss public policies focused on family farming. Firstly, there are public food purchases, as instruments to encourage the purchase of products from family farming, such as the Food Acquisition Program (PAA), Institutional Purchases and the National School Feeding Program (Pnae). These programs aim to support sustainable agricultural production and the acquisition of diversified foods, considered to be of food value (GRISA; SCHNEIDER; VASCONCELLOS, 2020). This last fact can respond to actions driven by the National Plan for Agroecology and Organic Production (Planapo) by publishing the lists of socio-diversity products in 2016 and 2018 for commercialization in public food purchases (MOURA et al., 2020). Planapo is the instrument of the National Policy on Agroecology and Organic Production (PNAPO). Its first stage was carried out in the period 2013-2015 and its second execution was in the period from 2016 to 2019. Planapo aims to articulate the actions between public and private agents to encourage agroecology in Brazil, in which the diversification of cultures makes a fundamental part of agro-ecological practices. Therefore, both institutional purchases and Planapo have contributed to the increase in the sale of diversified products in family farming.

5. Conclusions

The impact of extreme weather events on crop diversification in Brazil shows the following effects. First, the results showed that diversification was adopted as an adaptation strategy by Brazilian AMCs when the climatic shocks were the longest period of annual drought, days without precipitation and hot days. It is noteworthy that the evolution of the percentage of hot days and the average annual temperature had increasing trends over the period from 1985 to 2016. Then, diversification was not considered as a practice to mitigate the vulnerability caused by frosts in the South region and heavy rainfall. However, the very heavy rainy days had a decreasing trend in all Brazilian regions over the same period, while the frosts had an erratic behavior. Thus, it can be concluded that the response to diversification as an adaptive strategy would depend on the type of climate shock.

The results of simulations of the rate variation in Brazilian crop diversification in the beginning (2016-2035) and mid (2046-2065) of the 21st century shows the following forecast. In the first period, all climate specifications showed a decrease in the percentage variation of Brazilian agricultural diversification, especially in the RCP8.5 scenarios. However, the decrease in Brazilian diversification in the period 2016-2035 would be less than the historical average observed (-8.7%) in the period from 1996 to 2017. Next, the variation in diversification would increase in the scenario of high GHG emissions (RCP8.5) in the second period (2046-2065). These forecasts of changes in agricultural land use in Brazil indicate convergence to agricultural systems that are more resilient to climate change. However, there is a possibility that a change in diversification at regional levels does not necessarily imply a similar change in the degree of diversification in the scale of farm. Yet, it is assumed that the contribution of individual activities impacts diversification with data at the regional level.

Finally, it is primordial role of investment in research related to sustainable technologies, such as crop diversification, to be able to follow the extension and rural credit. Furthermore, there is a need for the development of equipment and machinery coupled with the reality of diversified agricultural systems in different Brazilian biomes. Thus, it is also essential to train ecologically based operators, technicians and farmers in order to take advantage of the services of biological diversity, through positive agro-ecological interactions that help the reduction of climatic risks.

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